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Greenhouse gas emissions from Indian rice fields: calibration and upscaling using the DNDC model

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Abstract

Crop growth simulation models provide a means to quantify the effects of climate, soil and management on crop growth and biogeochemical processes in soil. The Denitrification and Decomposition (DNDC) model was evaluated for its ability to simulate methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) emissions from Indian rice fields with various management practices. The model was calibrated and validated for field experiments in New Delhi, India. The observed yield, N uptake and greenhouse gas (GHG) emissions were in good agreement with the values predicted by the model. The model was then applied for estimation of GHG emissions from rice fields in India using a newly compiled soil/climate/land use database. Continuous flooding of rice fields (42.25 million ha) resulted in annual net emissions of 1.07–1.10, 0.038–0.048 and 21.16–60.96 Tg of CH_4-C, N_2O-N and CO_2-C, respectively, with a cumulated global warming potential (GWP) of 130.93–272.83 Tg CO_2 equivalent. Intermittent flooding of rice fields reduced annual net emissions to 0.12–0.13 Tg CH_4-C and 16.66–48.80 Tg CO_2-C while N_2O emission increased to 0.056–0.060 Tg N_2O-N. The GWP, however, reduced to 91.73–211.80 Tg CO_2 equivalent. The study suggests that the model can be applied for studying the GHG related issues in rice cropping systems of India.

1. Introduction

The production of rice in South Asia, including India, has increased markedly with the introduction and widespread adoption of modern crop production technologies such as early maturing and N responsive semi-dwarf cultivars; high use of inorganic fertilizers, especially N fertilizers, and pesticides; and the expansion of irrigation facilities. Most of the rice in monsoonal Asia is grown as a transplanted crop in wet season from July to October (known as kharif season in India), where fields are flooded before planting and the soil is puddled to reduce percolation. The chemical environment of reduced soil and the extremely limited O_2 supply in the soil-floodwater system has a large influence on the soil nutrient dynamics of irrigated rice systems.

Carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are the important greenhouse gases (GHG) contributing 60, 15 and 5%, respectively, towards enhanced global warming (Watson et al., 1996). Concentrations of these gases are increasing at 0.4, 3.0 and 0.22% per year, respectively (Battle et al., 1996). Apart from causing global warming N_2O is also responsible for the destruction of the stratospheric ozone (Rodhe, 1990). Quantification of GHG emission from soil is needed for global modelling studies in the context of ecosystem modification and climate change (Li et al., 1997). Global and regional estimates of GHG emission from rice paddy fields vary greatly with the assumptions made on the importance of different factors affecting the emissions. Only a few studies (Bachelet and Neue, 1993; Mathews et al., 2000a, b; Li et al., 2004) have attempted to calculate detailed regional GHG emissions.

Several models have been developed in recent years to predict emissions of CH_4 and N_2O from agricultural fields. Early models used regression relationships between rates of emissions and either the crop biomass (Kern et al., 1997) or grain yield (Anastasi et al., 1992). These relationships were based on the assumption that higher the biomass production of the crop, the more substrate would be available for CH_4 production, either from increased crop residues or from higher rates of rhizo-deposition. Cao et al. (1995) presented a more differentiated approach describing CH_4 production and oxidation in rice fields. In this model, soil organic carbon (SOC) was assumed to be partitioned between three main pools based on their rates of decomposition. The seasonal pattern of redox potential (Eh) was required as an input in the model. Huang et al. (1998) used two pools in their model to represent soil organic matter, with different potential decomposition rates for each; these were modified by multipliers representing the influence of soil texture and temperature. As with the Cao et al. (1995) model, CH_4 production was affected directly by soil Eh, although this was simulated rather than used as a model input. Lu et al. (2000) developed a model for CH_4 production derived from incubation studies. Matthews et al. (2000a, b) developed MERES (Methane Emission in

Rice EcoSystems) model for simulating CH_4 emissions from rice fields. The model was based on CERES-Rice model but did not cover N_2O or CO_2 emissions. Other models, however, include the entire set of GHG, for example, CENTURY (Parton, 1996), DNDC (Li, 2000) and InfoCrop (Aggarwal et al., 2004), but are not yet at a stage where their predictive ability is satisfactory. Moreover, the models have hardly been used in tropical regions. The objectives of the present study were to evaluate the DNDC model for its ability to simulate (1) GHG emissions and global warming potential (GWP) of rice fields with different management practices and (2) GHG emissions from the various rice-growing regions of India.

2. Materials and methods

2.1. Description of the DNDC model

The Denitrification-Decomposition (DNDC) model (Li, 2000) is a generic model of C and N biogeochemistry in agricultural ecosystems. The model simulates C and N cycling in agro-ecosystems at a daily or sub daily time step. It consists of six interacting submodels: soil climate, plant growth, decomposition, nitrification, denitrification and fermentation (Li et al., 1997). In DNDC, SOC resides in four major pools: plant residue (i.e., litter), microbial biomass, humads (or active humus), and passive humus. Each pool consists of two or three sub-pools with different specific decomposition rates. The soil climate submodel simulates soil temperature and moisture profiles based on soil physical properties, daily weather and plant water use. The plant growth submodel calculates daily water and N uptake by vegetation, root respiration, and plant growth and partitioning of biomass into grain, stalk and roots. The decomposition submodel simulates daily decomposition, nitrification, ammonia volatilization and CO_2 production by soil microbes. The submodel calculates turnover rates of soil organic matter at a daily time step (Li et al., 1994). The nitrification submodel tracks growth of nitrifiers and turnover of ammonium to nitrate. The denitrification submodel operates at an hourly time step to simulate denitrification and the production of nitric oxide (NO), N_2O, and dinitrogen (N_2). The fermentation submodel simulates CH_4 production and oxidation under anaerobic conditions. The DNDC model has been widely used over the last 10 years by many researchers (Brown et al., 2002; Butterbach-Bahl et al., 2004; Cai et al., 2003; Li et al., 1997, 2000, 2004; Smith et al., 2002, 2004). Simulated results showed that DNDC was able to simulate the basic patterns of NO, N_2O, CH_4 and NH_3 fluxes simultaneously (Li, 2000). This feature could be valuable in assessing the net effect of the changing climate or alternative agricultural management on either the atmosphere or agriculture.

Recently the DNDC model has been modified for predicting GHG emissions from paddy rice ecosystems (Li et al., 2004). The majority of the modifications focused on simulations of anaerobic biogeochemistry and rice growth as well as parameterization of paddy rice management. The modified model was tested for its sensitivities to management alternatives and variations in natural conditions including weather and soil properties. When estimating GHG emissions under specific management conditions at regional scale, the spatial heterogeneity of soil properties (e.g., texture, SOC content, pH) are the major sources of uncertainty. An approach, the most sensitive factor (MSF) method, was developed for DNDC to reduce the magnitude of uncertainty (Li et al., 2004). The modified DNDC model was used for estimating emissions of CO_2, CH_4, and N_2O from all of the rice paddies in China with two different water management practices, i.e., continuous flooding and midseason drainage that were the dominant practices before 1980 and in 2000, respectively (Li et al., 2004). In the present study this modified model was further refined to simulate emissions of CO_2, CH_4, and N_2O under the conditions found in rice paddies of India.

2.2. Model modification

Modifications were made for the DNDC model to improve its performance in simulating crop yield and CH_4 emissions for Indian rice fields. Most of the crop physiological and phenological parameters set in the DNDC model were originally calibrated against datasets observed in the U.S., China or other temperate regions. Discrepancies appeared when the model was applied for the rice crops in India. Modifications were made with the accumulative thermal degree-days as well as the growth rates of vegetative and reproductive stages to adjust the rice-growing season. These modifications have improved the model's capacity for predicting crop yields in India.

Low CH_4 fluxes were measured in some rice paddies in India (Pathak et al., 2003), which were not adequately captured by the model originally. Test runs for the sites where the low CH_4 fluxes were not captured by DNDC indicated that these sites had relatively high leaking rates. The leaking processes embedded in the model were modified to let the process lead to not only water but also substrates e.g., dissolved organic carbon (DOC) and nitrate loss from the paddy soils. This modification has substantially decreased CH_4 emissions from the sites with high leaking rates. A graphic interface was built in the DNDC model to browse the regional database as well as to map the modeled results e.g., crop yield, C sequestration, CH_4 or N_2O emissions for India.

2.3. Model calibration

Two field experiments were used for the calibration of the model (Pathak et al., 2002, 2003). The experiments were done at the experimental farm of the Indian Agricultural Research Institute, New Delhi, India. The site is located at 28°40′ N and 77°12′ E, subtropical, semi-arid, with annual rainfall of 750 mm. The mean maximum and minimum temperatures from July to October (rice season) are 35 and 18°C, and 22.6 and 6.7°C from November to April (wheat season). The alluvial soil of experimental site was sandy loam in texture and has organic carbon, total N, Olsen P, and ammonium acetate extractable K contents of 4.5 g kg^{-1}, 0.30 g kg^{-1}, 0.007 g kg^{-1}, and 0.13 g kg^{-1}, respectively. The soils are well drained with the groundwater table at 6.6 and 10 m deep during the rainy and summer seasons, respectively.

The experiments included treatments varying in N sources and water management in plots of 6 m long and 5 m wide. Three, 30 days old rice seedlings (cultivar Pusa

44) were transplanted at 20 cm (row to row) by 15 cm (hill to hill) spacing on 15 July 1999. Emissions of CH_4 and N_2O were measured frequently from the plots following the standard methodologies (Pathak et al., 2002, 2003). Total dry matter, grain yield and N uptake were measured at maturity.

The genetic coefficients for rice cultivar, used as model inputs to describe crop phenology in response to temperature and photoperiod, were estimated from independent treatments with water and N non-limiting by adjusting the coefficients until close matches were achieved between simulated and observed phenology and yield. Total thermal time requirement for rice cultivar found to be 2250°C. Rate constants of crop development in vegetative and reproductive stages were 0.015 per day and 0.044 per day.

2.4. Sensitivity analyses

Sensitivity of the model to the changes in amount of N fertilizer and irrigation applications on rice yield and GHG emissions was analysed using the baseline data (weather, soil, cultivar, location and other inputs) of year 1999 of the experiment.

2.5. Global warming potential

Global warming potential (GWP) is an index defined as the cumulative radiative forcing between the present and some chosen later time 'horizon' caused by a unit mass of gas emitted now. It is used to compare the effectiveness of each greenhouse gas to trap heat in the atmosphere relative to some standard gas, by convention CO_2. The GWP for CH_4 (based on a 100-year time horizon) is 21, while that for N_2O, it is 310 when GWP value for CO_2 is taken as 1. The GWP of different treatments were calculated using the following equation (Watson et al., 1996).

$$\mathrm{GWP} = CO_2 \text{ emission} + CH_4 \text{ emission} * 21 + N_2O \text{ emission} * 310$$

2.6. Upscaling GHG emissions from rice growing areas in India

The approach for the upscaling GHG emissions using the DNDC model and geographical information system (GIS) are depicted in Fig. 1. The required input parameters of the DNDC model consisting of daily meteorological data (maximum and minimum temperatures, precipitation and solar radiation), soil properties (SOC, clay contents, pH and bulk density) and field area under different rice ecosystems (irrigated lowland, rainfed lowland, rainfed upland and deepwater) were compiled in a GIS database. India is divided into several states and the states are further divided into different administrative boundaries called districts. Since many of the statistical data were district-based, district was chosen as the basic geographic unit of the database to maintain the maximum accuracy of the original data sets. The meteorological data was obtained from National Climatic Data Center, USA and consisted of daily records of more than 110 climatic stations across India. Soil properties were compiled from NBSS and LUP (1998), Velayutham and Bhattacharya (2000) and Kalra (personal communication, 2004). Field area under the four major rice ecosystems (irrigated lowland, rainfed lowland, rainfed upland and deepwater) in the different districts of the country was compiled from published data (FAI, 2000; FAO, 2000; Yadav and Subba Rao, 2001; Bhatia et al., 2004). For irrigated lowland and rainfed lowland rice systems simulation was done for two irrigation practices: 1) continuous flooding and 2) intermittently flooding during the cropping season. In both the cases 120 kg N ha^{-1} per season was applied through urea, broadcast at 3 splits ($\frac{1}{2}$ at 1 DAT, $\frac{1}{4}$ at 30 DAT and $\frac{1}{4}$ at 55 DAT). In case of rainfed upland system no irrigation was applied and the fields were never flooded while for deepwater rice system fields were kept continuously submerged with water. For the latter two systems 64 kg N ha^{-1} was applied through urea, broadcast at 2 equal splits at 1 and 30 DAT, respectively as per the practice commonly followed by the farmers. For all the systems field was ploughed 3 times with moldboard plough before rice transplanting. The model calculated annual CO_2, CH_4, and N_2O fluxes from each rice ecosystem for two scenarios: (1) minimum emission and (2) maximum emission. The scenario for minimum emission includes the minimum values of SOC, pH and bulk density and the maximum value of clay content of soil while the scenario for maximum emission includes the maximum values of SOC, pH and bulk density and the minimum value of clay content of soil.

3. Results and discussion

3.1. Evaluation of the model

Predicted grain and biomass yields and N uptake agreed well with observed values (Table 1). The observed emission of CH_4 during the growing season was 28 kg C ha^{-1}, while the simulated emission was 27 kg ha^{-1}. Emission of N_2O was 0.74 kg N_2O-N ha^{-1} while the simulated value was 0.69 kg N_2O-N ha^{-1}. In all the cases the deviation of the simulated value from the observed value was less than 5% except in case of N_2O emission when the deviation was 6.8% (Table 1).

3.2. Sensitivity analysis for impacts of N and water management on yield, N uptake and GHG emission

Different levels of N significantly influenced the simulated yield, N uptake and emissions of GHG from soil (Table 2). Grain yield of rice as well as N uptake increased with application rate up to 300 kg N ha^{-1}, but with smaller increases at rates above 180 kg ha^{-1}. Emissions of CO_2 and CH_4 increased considerably from 0 to 120 kg N ha^{-1} because of more shoot and root growths of rice with N application producing more amounts of root exudates and larger amounts of root debris, which supplied C as substrate heterotrophic microbes for resulting in larger CO_2 and CH_4 emissions. Further increase in N levels i.e., from 180 to 300 kg N ha^{-1} had little influence on the emissions because of their limited additional influence over 120 kg N ha^{-1} on rice growth. Emission of N_2O, however, remained unchanged up to 180 kg N ha^{-1}. As the fields were continuously flooded keeping them anaerobic throughout the growing period, the process of nitrification producing NO_3^- from NH_4^+ was stopped, and as a result denitrification was also inhibited because of non-availability of substrate (NO_3^-) for this process. These two processes i.e., nitrification and denitrification are mainly responsible for the formation of N_2O in soil (Duxbury et al., 1982). However, application of more than 180 kg N ha^{-1} through urea increased N_2O emission because larger fluxes of NH_4^+-N.

Substituting 60 kg ha^{-1} chemical N with farmyard manure (FYM) reduced grain yield and N uptake by rice but increased GHG emissions as compared to application of 120 kg N ha^{-1} through urea alone. Addition of organic C through FYM was responsible for such increase in the GHG emissions (Adhya et al., 2000; Pathak et al., 2002).

Water management also influenced the simulated yield, N uptake and emissions of GHG from soil (Table 2). Treatments with continuously flooding gave higher yield, N uptake, and CH_4 and CO_2 emissions compared to midseason drainage treatments. Emission of CH_4 reduced by 31% and 54% with 1 and 2 midseason drainages of 10 days each compared to that under continuously flooded soil. Nitrous oxide emission, on the other hand increased marginally with midseason drainage, which resulted in aerobic condition of soil with enhanced nitrification forming N_2O and NO_3^--N. It also enhanced denitrification by supplying the substrate (NO_3^-) for the denitrifiers resulting in more N_2O emission when the field was reflooded (Aulakh et al., 1992).

The CH_4 emission values simulated in this study are similar to that reported by Jain et al. (2000) and Adhya et al. (2000) for Indian rice fields. However, emission was smaller compared to that reported from many other countries such as Philippines (Corton et al., 2000) and Japan (Yagi et al., 1996). Lower CH_4 emission from Indian rice paddies compared to that of other countries are due to 1) lower soil organic C status, 2) high percolation rate of sandy loam soils, which allows to leach substantial amount of dissolved organic C (DOC) to lower soil profiles, 3) lower yield of rice with smaller rhizo-deposition and 4) limited amount of organic residue recycling in soil.

Daily emission pattern of CH_4 revealed that emission was recorded only during the period of flooding (Fig. 2). Flux of CH_4 varied between 0 to 3.62 kg C ha^{-1} day^{-1}. Continuous flooding emitted more CH_4 than the midseason drainage and application of FYM enhanced the emission.

Annual emission of N_2O showed that there were several peaks of fluxes (Fig. 3). Emission of N_2O-N ranged from 0 to 112.3 g ha^{-1} day^{-1} during the year. Initial high peak of N_2O emission was due to nitrification of ammonium-N present in soil. Subsequent peaks corresponded to the rainfall and flooding events, which resulted in denitrification of soil NO_3.

3.3. Upscaling of GHG emission from Indian rice fields

3.3.1. Database of soil and rice ecosystems

The spatial distribution of SOC, clay contents, pH and bulk density of soils in different rice growing regions of India at the district scale are presented in Fig. 4. Being in the tropical region, the SOC contents of soil is low varying from <0.2% to 1%, with majority of soils containing SOC<0.6% (Fig. 4a). Clay contents of soil varied between 10 to 67%. The soils of north India are lighter in texture while those of central and west India are heavier in texture (Fig. 4b). Majority of soils in India are alkaline in pH (pH>7.5) with soils in eastern India are acidic to neutral in reaction (Fig. 4c). The soils of north India have higher bulk density as compared to those from the rest of the country (Fig. 4d).

There are mainly four major rice ecosystems in India (1) irrigated lowland, (2) rainfed lowland, (3) rainfed upland and (4) deepwater covering an area of 42.25 M ha (Table 3). Half of the area (21.41 M ha) is under irrigated lowland and 14.45 M ha is under rainfed lowland rice ecosystems. Upland rice is grown in 4.2 M ha of land while deepwater rice occupies an area of 2.22 M ha. In lowland ecosystems rice seedlings are transplanted in puddled condition and the fields are kept either in continuous submergence or intermittently flooded depending on soil texture, rainfall and availability of irrigation water. Lowland rice fields in north India are generally intermittently flooded while those from east and south India are flooded continuously. In case of upland rice the seeds are directly sown on pulverized seedbed and fields are never flooded. Deepwater rice is grown in low-lying high rainfall areas, where fields are inundated with water. In these areas rice is either direct seeded or transplanted depending upon the onset of monsoon.

3.3.2. Emission of GHG

The modeled results indicated that total CH_4 flux from the simulated 42.25 million ha of rice in India ranged from 1.07 to 1.10 Tg C per year under continuous flooding conditions (Table 4). With the intermittent flooding scenario, the national CH_4 flux from rice fields reduced to 0.12–0.13 Tg C per year implying that the water management change in India drastically reduced CH_4 fluxes. Intermittent flooding approach has been applied in many Asian countries such as India (Jain et al., 2000; Adhya et al., 2000), Philippines (Corton et al., 2000), China (Li et al., 2002), and Japan (Yagi et al., 1996) to reduce CH_4 emissions.

With continuous flooding N_2O emission ranged from 0.038 to 0.048 Tg N per year (Table 4). Shifting the water management from continuous flooding to intermittent flooding increased N_2O fluxes to 0.056–0.060 Tg N yr^{-1}. But like CH_4 emission, emission of CO_2 reduced with intermittent flooding. The upscaling study for India, thus, revealed the complexity of GHG mitigation. When CH_4 and CO_2 emissions were reduced due to intermittent flooding, N_2O emission increased. Since N_2O possesses higher GWP, the increased N_2O offset the benefit gained by decreasing CH_4 and CO_2 fluxes. However, total GWP of rice growing areas decreased from 130.93–272.83 Tg CO_2 yr^{-1} with continuous flooding to 91.73–211.80 Tg CO_2 yr^{-1} with intermittent flooding.

The simulated spatial distribution of GHG emissions from Indian rice fields and their GWP under continuous flooding condition is shown in Fig. 5. Emission of CH_4 ranged from <10 kg CH_4-C ha^{-1} to >70 kg CH_4-C ha^{-1} (Fig. 5a). The maximum emission value was 106 kg CH_4-C ha^{-1}. High emission values in some of the districts in north-west India could be due to high temperature (>40°C) in the region during the rice growing season. Regions in the eastern India also showed higher emission because of high temperature and high SOC content compared to those from western part of the country.

Emission of N_2O from the various rice ecosystems of India ranged from <0.5 g N_2O-N ha^{-1} to >2.0 g N_2O-N ha^{-1} (Fig. 5b) while emission of CO_2 varied between <600 to >2400 kg CO_2-C ha^{-1} (Fig. 5c) under continuous flooding condition. Unlike CH_4, emissions of N_2O were higher from the south-western regions of the country while the regions in the eastern and south eastern India showed higher CO_2 emission, similar to that of CH_4 because of high temperature and high SOC content in these regions. The northern, eastern and southern parts of the country showed higher GWP (Fig. 5d), mainly because of higher CH_4 and CO_2 emissions. The GWP of the rice growing regions through out the country was <2000 to >8000 kg CO_2equivalent per year.

4. Conclusions

The DNDC model was generally able to encapsulate the major impacts of water and N on rice crop performance and GHG emissions in tropical soils. The analysis suggested that the model can be applied for studying the GHG related issues in rice cropping systems of India. A trade-off between CH_4 and CO_2 emissions and N_2O emission was observed. The conflict between the CH_4, $CO_2$and N_2O mitigation measures demonstrated the challenge of mitigating GHG emissions through managing biogeochemical cycles in terrestrial ecosystems. Therefore, new tools for land-use analysis and planning are needed to reconcile the legitimate aims of improving water and N management and reducing GHG emission from agricultural fields. Models such as DNDC would be very useful to accelerate the application of available knowledge at field, farm and regional levels for optimizing agronomic management, quantifying changes in SOC and GHG emissions with changing land use, and developing mitigation options for GHG emissions.

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Table 1. Observed and simulated records on harvested yield and biomass as well as N uptake and GHG emission from rice fields in Northern India applied with 120 kg urea N ha^{-1}.

Parameters	Observed (kg ha^{-1})	Simulated (kg ha^{-1})	Deviation (%)
Grain yield (kg ha^{-1})	6800	6815	0.2
Total biomass (kg ha^{-1})	17 436	17 718	1.6
Crop N uptake (kg N ha^{-1})	126	128	1.6
Seasonal CH_4 emission (kg CH_4-C ha^{-1})	28	27	3.6
Seasonal N_2O emission (kg N_2O-N ha^{-1})	0.74	0.69	6.8

Table 2. Sensitivity analysis for different rates of N application, water regimes and manure application affecting simulated rice yields, N uptake and annual GHG emissions.

Urea N	Water regime[a]	Grain yield (kg ha^{-1})	N uptake (kg N ha^{-1})	CO_2 emission (kg C ha^{-1})	CH_4 emission (kg C ha^{-1})	N_2O emission (kg N ha^{-1})
0	CF	1775	33	712	40	1.85
60	CF	4798	90	741	81	1.85
120	CF	7320	137	760	96	1.85
180	CF	9015	169	771	101	1.85
240	CF	10 015	188	774	103	1.89
300	CF	10 868	204	768	103	2.12
60 (+60)[b]	CF	6633	124	1665	120	1.88
120	1MD	7210	135	690	66	1.93
120	2MD	7075	133	617	42	1.96

[a] CF = continuous flooding; 1MD and 2MD = 1 and 2 midseason drainages, respectively
[b] plus 60 kg N from farmyard manure

Table 3. Areas under the various rice ecosystems in different states of India.

State	Area (million ha)				
	Irrigated lowland	Rainfed lowland	Rainfed upland	Deepwater	Total
Andhra Pradesh	3.45			0.07	3.52
Arunachal Pradesh	0.04	0.08			0.12
Assam	0.53	1.60	0.22	0.10	2.45
Bihar	1.93	1.59	0.53	0.67	4.72
Goa	0.01	0.09			0.10
Gujarat	0.40	0.22			0.62
Haryana	0.79				0.79
Himachal Pradesh	0.05		0.03		0.08
Jammu and Kashmir	0.25		0.02		0.27
Karnataka	0.87	0.04	0.39		1.30
Kerala	0.27	0.08	0.15		0.50
Maharashtra	0.42		0.79	0.32	1.53
Manipur	0.08	0.09			0.17
Meghalaya	0.05	0.06			0.11
Mizoram	0.01	0.06			0.07
Madhya Pradesh	1.23	3.82			5.05
Nagaland	0.06	0.07			0.13
Orissa	1.61	2.00	0.69	0.15	4.45
Pondicherry	0.03				0.03
Punjab	2.24	0.03			2.27
Rajasthan	0.05	0.11			0.16
Sikkim	0.02				0.02
Tamil Nadu	2.06	0.27			2.33
Tripura	0.05	0.21			0.26
Uttar Pradesh	3.37	1.33	0.50	0.23	5.43
West Bengal	1.53	2.68	0.88	0.68	5.77
Total	**21.41**	**14.45**	**4.20**	**2.22**	**42.25**

Table 4. Annual GHG emissions from Indian rice fields under continuous flooding and midseason drainage practices.

Parameter	Continuous flooding		Midseason drainage	
	[a] Minimum	[b] Maximum	Minimum	Maximum
CH_4 emission (Tg C yr^{-1})	1.07	1.10	0.12	0.13
N_2O emission (Tg N yr^{-1})	0.048	0.038	0.060	0.056
CO_2 emission (Tg C yr^{-1})	21.16	60.96	16.66	48.80
GWP (Tg CO_2 equiv. yr^{-1})	130.93	272.83	91.73	211.80

[a] Scenarios for minimum emission: Minimum of SOC, pH and bulk density and maximum of clay content of soil.
[b] Scenarios for maximum emission: Maximum of SOC, pH and bulk density and minimum of clay content of soil.

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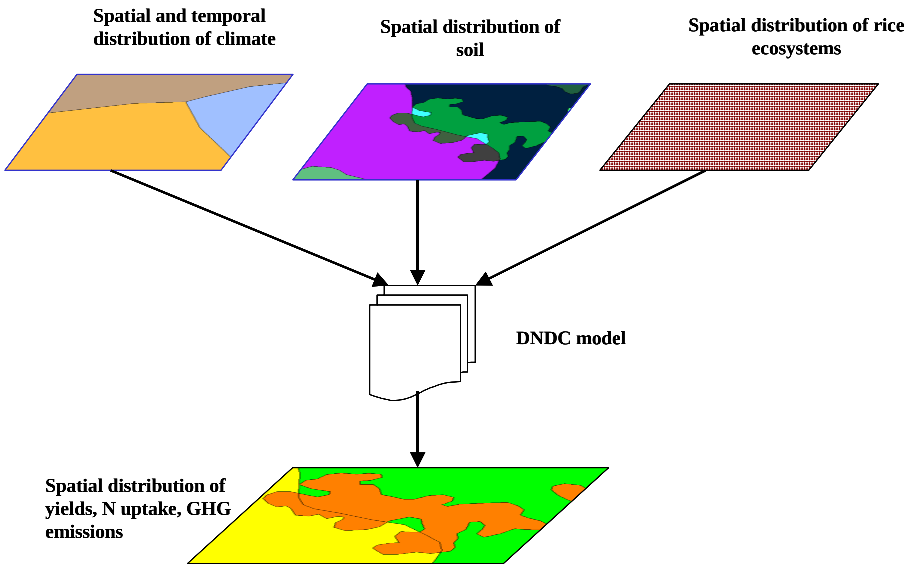


Fig. 1. Approaches for the upscaling of greenhouse gas emission from rice fields in India using the DNDC model.

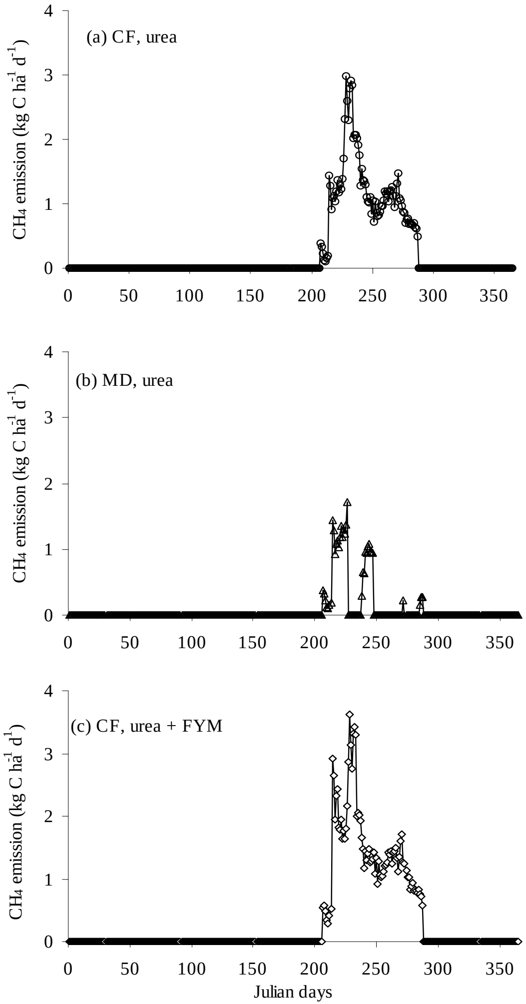


Fig. 2. Effect of continuous flooding (CF), midseason drainage (MD) and farmyard manure (FYM) on simulated methane emission.

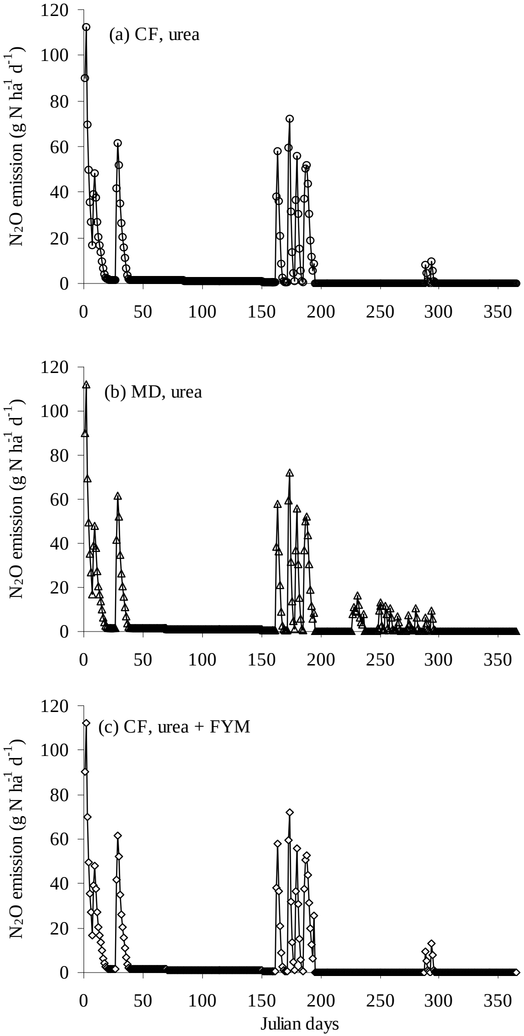
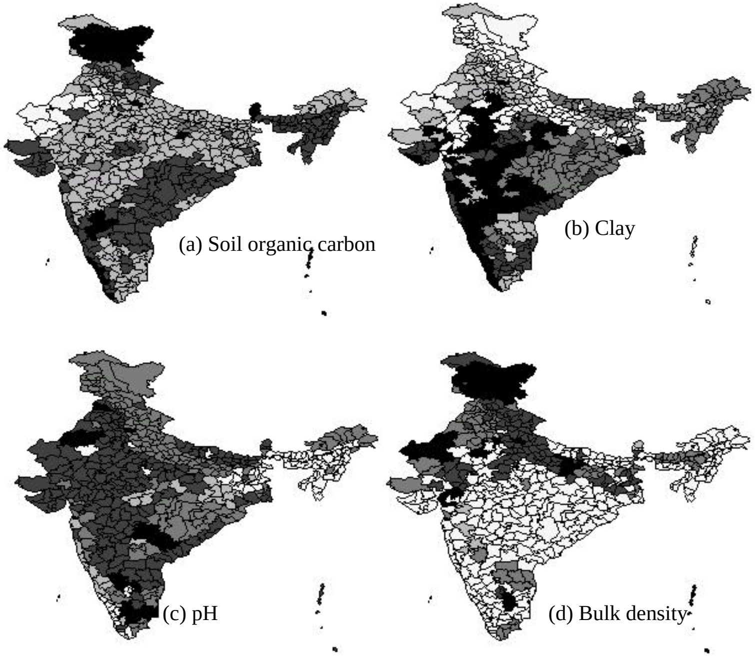
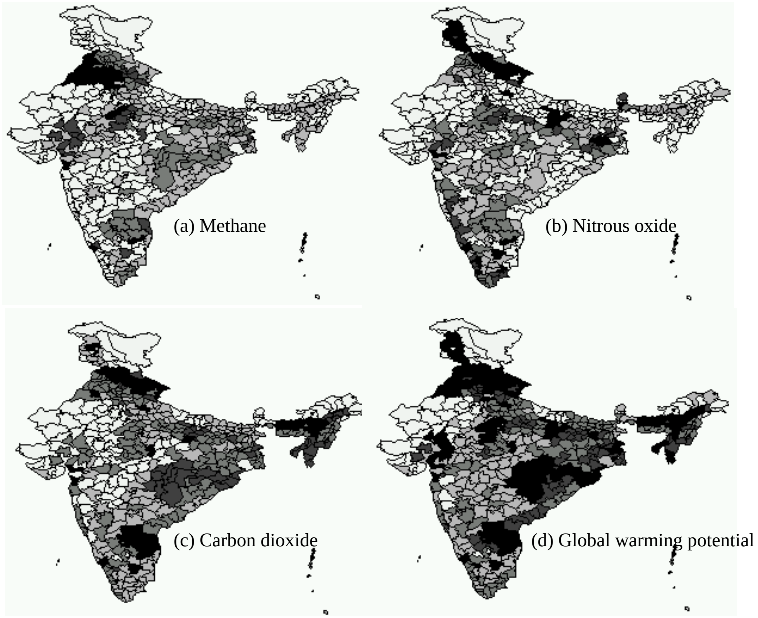


Fig. 3. Effect of continuous flooding (CF), midseason drainage (MD) and farmyard manure (FYM) on simulated nitrous oxide emission.



Legend	(a) Soil organic C (%)	(b) Clay (%)	(c) pH	(d) Bulk density (Mg m^{-3})
(white)	<0.2	<20	<5.5	<1.35
(light grey)	0.2-0.4	20-30	5.5-6.5	1.35-1.40
(grey)	0.4-0.6	30-40	6.5-7.5	1.40-1.45
(dark grey)	0.6-0.8	40-50	7.5-8.5	1.45-1.50
(black)	>0.8	>50	>8.5	>1.50

Fig. 4. Spatial distribution of organic carbon, clay contents, pH and bulk density of soils of India. Legends of the figures are given below.



Legend	(a) CH_4 ($kg\ CH_4\text{-}C\ ha^{-1}$)	(b) N_2O ($kg\ N_2O\text{-}N\ ha^{-1}$)	(c) CO_2 ($kg\ CO_2\text{-}C\ ha^{-1}$)	(d) GWP ($kg\ CO_2\ ha^{-1}$)
	<10	<0.5	<600	<2000
	10-30	0.5-1.0	600-1200	2000-4000
	30-50	1.0-1.5	1200-1800	4000-6000
	50-70	1.5-2.0	1800-2400	6000-8000
	>70	>2.0	>2400	>8000

Fig. 5. Annual emissions of methane, nitrous oxide, carbon dioxide and global warming potential of rice systems of India under continuous flooding condition. Legends of the figures are given below.